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APPLICATION OF PENETROMETERS TO THE STUDY OF PHYSICAL PROPERTIES OF LUNAR AND PLANETARY SURFACES

by John Locke McCarty, Alfred G. Beswick, and George W. Brooks

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SUMMARY

A study was made to evaluate the practicality of employing the penetrometer technique as a means for determining physical characteristics of a remote surface such as that of the moon or a planet. The study included a review of the history and fundamentals of the penetrometer concept and an examination of the basic requirements for penetrometers and necessary support apparatus.

Results of the study indicate that practical penetrometer systems can be employed to determine such surface properties as hardness or penetrability and, possibly, bearing strength. Design considerations are given for a penetrometer system which requires further development and also for penetrometer systems presently attainable but which introduce some complexity and which may impose some limitations on the attainment of experimental goals. Design considerations of support apparatus required for some missions are also presented.

The applicability of penetrometer concepts and techniques to various present-day manned and unmanned spacecraft is discussed. In addition, details of a specific application of the concept as a payload for the Ranger spacecraft are appended.

INTRODUCTION

The exploration of the moon is a primary objective of current and future space programs. In the past, scientists have made good use of optical and electromagnetic techniques to accumulate information on the large-scale characteristics of the lunar surface, such as the size and distribution of craters and mountains. However, few data exist which define small-scale lunar features such as surface texture and topographical detail. A knowledge of small-scale characteristics is of primary importance since it is these properties which will determine the abilities of exploratory vehicles to land and move about on the surface. The lack of such information is due to the inability of earth-based instrumentation to directly measure the quantities of interest with the required resolution. Thus, it appears that data defining the lunar surface characteristics must be obtained by instruments operating on or near the lunar surface.

The Langley Research Center has been interested in the problem of measuring physical properties of the lunar surface for some time and has been actively seeking means by which this might be effectively accomplished. This endeavor indicated that a good approach to the problem would be to measure directly the desired surface properties by a well-understood technique which provides the data in a form that allows comparison with the physical properties of known earth materials. A program within the framework of these guidelines was initiated to evaluate a technique for determining certain physical properties of the lunar surface such as hardness, bearing strength, and penetrability. The technique consisted of impacting acceleration measuring instruments onto the surface and analyzing the accelerations generated during the impact process. Consequently, a laboratory study was undertaken to relate certain physical characteristics of terrestrial surfaces to acceleration signatures measured during impact of suitably instrumented projectiles onto those surfaces. The scope of this test program, summarized in table I, included the study of the impact characteristics of various metallic projectiles over two velocity ranges on a wide variety of target materials. Measurements were taken of the impact acceleration and dimensions of the resulting craters. The results of this study, presented in reference 1, indicated that sufficient information can be derived from impact acceleration time histories to define adequately the nature of the target material. Thus, it appears that certain properties such as hardness or

TABLE I

SCOPE OF IMPACT TESTS

[Summarized from ref. 1]

Test velocity	Target	Test variables (projectile)	Measurements
Low range (5-40 fps)	Concrete Lead Balsa Sod Sand (00 grade) Peat moss Cement dust Peat moss and sand mixture	Mass Diameter	Acceleration time history Penetration depth Crater diameter
High range (100-900 fps)	Soil Concrete Peat moss Cement dust Layers: Peat moss on balsa Cement dust on soil	Mass Nose shape	For 100 to 240 fps: Acceleration time history Penetration depth For 240 to 900 fps: Peak acceleration Penetration depth

penetrability and, possibly, bearing strength of a remote target surface, such as the moon or a planet, could be described in terms of the properties of accessible earth materials. This description is accomplished by comparing the acceleration time histories measured during the impact of accelerometer-equipped projectiles on the remote surface with those of identical projectiles during impacts on known earth materials.

An investigation of the means of impacting such instrumented projectiles, hereinafter referred to as penetrometers, onto the lunar surface evolved from the results of the study reported in reference 1 and is presented in the present paper. Although this investigation is primarily concerned with lunar surface exploration, the technique is equally applicable to the exploration of planetary surfaces.

SYMBOLS AND NOMENCLATURE

a acceleration

a_{max} maximum acceleration encountered during impact process

h altitude above lunar surface

t arbitrary time

t_{2r} time with respect to ignition of secondary retrorocket motor

t_t total time for impact process

Penetrometer — impacting body equipped with an acceleration sensor and having the capability to transmit impact acceleration signals to a relay craft or a receiving station

Relay craft — vehicle designed to intercept and retransmit penetrometer impact acceleration signals to a remotely located receiving station

Receiving station — vehicle or earth site that receives, processes, stores, and utilizes acceleration signals from penetrometers

Penetrometer payload carrier — structure which houses and deploys penetrometers

BASIC CONCEPT, COMPONENTS, AND FUNCTIONS

Summary of Supporting Impact Research

The acceleration time histories recorded during the impact tests of reference 1 revealed various characteristics which define the nature of the impacted surface as well as the class of impact. These characteristics include the magnitude of the peak acceleration, the time required to reach that peak, the total duration of the acceleration process and the overall shape of the acceleration pulse. Figures 1 and 2 are presented to illustrate how a remote target can be evaluated from a knowledge of certain of these characteristics. In figure 1, taken from reference 2, the ratio of the measured peak accelerations to the impact velocity is plotted as a function of the measured total pulse time for a steel hemispherical projectile having a diameter of 2 inches and a weight of 1 pound impacting various target surfaces. The target surfaces, indicated in the figure, were chosen to be representative of the different impact categories - that is, elastic, plastic, or penetration, and combinations of these - and were not intended to be representative of any anticipated lunar or planetary surface media.

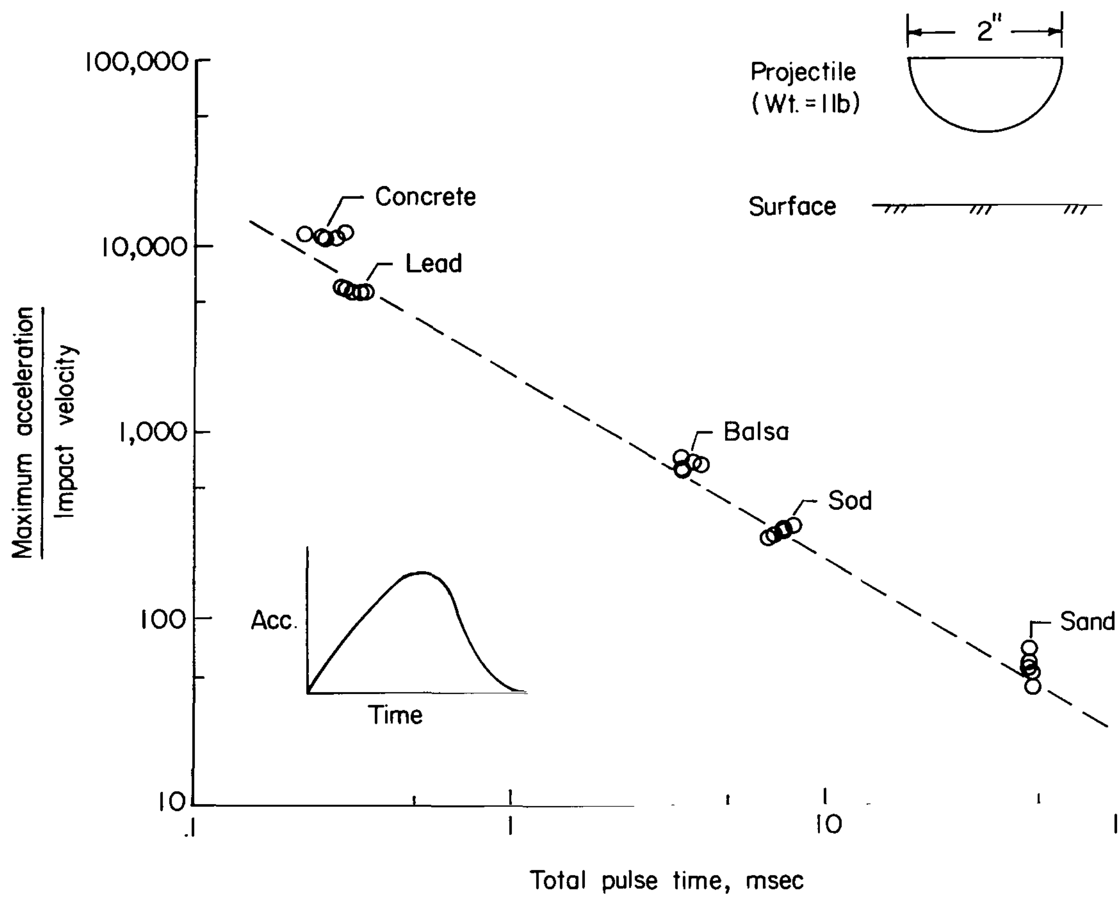
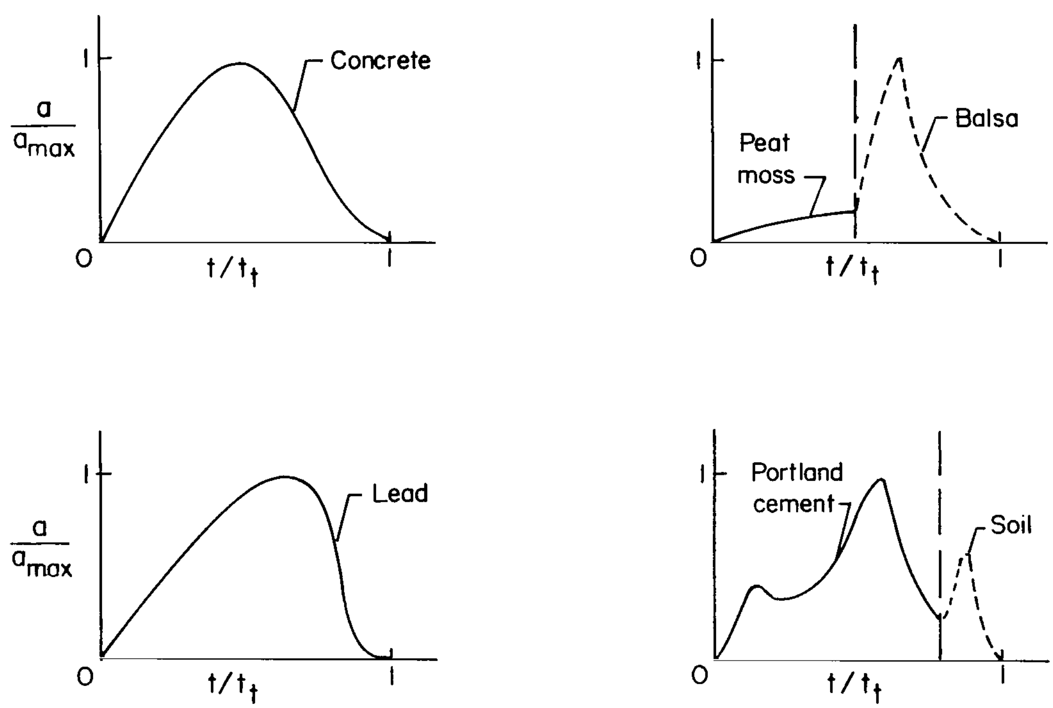


Figure 1.- Summary of impact data for a steel hemisphere.

The important facts shown by the data of figure 1 are as follows. If such a projectile is impacted on a remote surface, a good idea of the hardness of the surface may be obtained either by measuring the peak acceleration and the impact velocity or the total pulse time, since the magnitudes of these characteristics are dependent upon the target material. Hence, it appears that the hardness of lunar or planetary surfaces can be described in terms of the hardness of accessible earth materials from a knowledge of either of these impact characteristics. With the additional knowledge of the acceleration signature (pulse shape), the nature of the surface structure, including possibly the bearing strength and penetrability, can be defined. Analysis of the complete acceleration time history can also denote and describe strata configurations such as possible soft dust layers. As an illustration, sketches of acceleration time histories recorded during the impact of projectiles on several of the various target materials used in the impact investigation of reference 1 are presented in figure 2. Both the acceleration and time in this figure have been normalized: acceleration with respect to the maximum acceleration encountered during impact and time with respect to the total pulse time. Acceleration time histories are presented for an impacting body striking a material such as concrete which results in an essentially elastic collision producing an acceleration time history nearly symmetrical about a mean vertical line passing through the acceleration peak, a material such as lead which results in a plastic collision characterized by an acceleration time history with a brief restitution increment, and materials in two layer configurations which result in penetration of the projectile into the impacted medium.



(a) Continuous.

(b) Layers.

Figure 2.- General shapes of impact acceleration time histories.

The pulse shapes illustrated for the layer configurations resulted from impacts into loose peat moss on balsa and into a layer of ground portland cement on soil and serve to indicate the ability of the penetrometer technique to distinguish the layer characteristics of target materials.

From this brief review of the results of the impact studies, it is apparent that much information on the nature of lunar and planetary surfaces can be gained from an analysis of complete acceleration time histories recorded during the impact of penetrometers on those surfaces. Accordingly, consideration was given to the application of such devices as an experimental technique to evaluate characteristics of such remote surfaces and as a means for sounding those surfaces in support of manned landings. The following sections of the report are devoted to an examination of the operating principles and basic requirements of penetrometer devices and necessary accompanying support equipment which could be employed to obtain data on lunar and planetary surface characteristics.

Penetrometer

General considerations.- As discussed in the previous section, the impact technique for studying the physical properties of a remote surface relies upon the knowledge of certain characteristics of an impact acceleration time history or, more favorably, a complete record of the event. In order to obtain such information, the basic element required is a penetrometer equipped with a means of sensing the accelerations encountered by the body during the impact process.

For most practical applications it is desirable that the penetrometer be a self-contained operational device. Physical transmission links between the sensor and the penetrometer deploying structure, such as the trailing-wire systems of references 1 and 3, impose operational restrictions to such a technique. A technique appearing most attractive for practical application is to telemeter the acceleration information developed by the penetrometer by means of its own telemetry system to a nearby receiving station. Telemetering the information requires packaging a power supply, transmitter, and antenna system, in addition to the acceleration sensing device, within a casing capable of withstanding all anticipated impact loads. This technique permits the acquisition of acceleration data for all types of impact including high shock loadings and deep penetrations, provided that telemetry communication is maintained during the impact process. A discussion follows which briefly outlines design considerations for a penetrometer utilizing the telemetry technique.

Design considerations.- A penetrometer should have the capability of sensing impact accelerations and transmitting them to a receiving station regardless of its orientation during impact. Such a penetrometer would not require attitude stability and control nor elaborate deployment techniques. In addition, the data transmitted by such penetrometers would be valid despite surface topography. Adherence to these requirements alludes to a penetrometer of spherical design equipped with an omnidirectional acceleration sensor and an omnidirectional antenna. Some details of such a system are described in the appendix. The practical aspects of constructing such an omnidirectional penetrometer are limited by the capabilities of available acceleration sensors having truly omnidirectional characteristics. However, efforts are currently underway to develop accelerometers having or approximating omnidirectional capability. Sensors undergoing development include hydrodynamic sensors which sense pressure changes in a spherically confined fluid due to applied accelerations, electronic squaring and summing or direct algebraic summation of individual axis outputs of conventional piezoelectric triaxial accelerometers, and the summation of the individual outputs of multiple spherically distributed linear accelerometers. Other schemes providing or approximating omnidirectionality are conceivable; however, they appear to be either less compatible with the penetrometer concept or less advanced in their evolution.

It is apparent that the use of some of these sensors may produce acceleration measurement errors. For example, the direct algebraic summation of a triaxial accelerometer can result in errors which approach $\sqrt{3}$. However, if the surface properties of the moon were currently known to this accuracy, the design of spacecraft to land on such a surface would be a comparatively straightforward engineering problem.

Until a suitable omnidirectional accelerometer is available, other approaches offer attractive possibilities for penetrometer applications. Basically, such approaches use conventional instrumentation techniques but sacrifice omnidirectionality. One such approach is the use of unidirectional acceleration sensors. Penetrometers employing such devices may assume a wide variety of configurations such as, for example, the bullet-shaped penetrometer described in the appendix. However, any such unidirectional penetrometer must be properly oriented with respect to the target surface during impact, which introduces stringent attitude control requirements that are nonexistent in omnidirectional designs. Attitude control of unidirectional penetrometers for use on surfaces of celestial bodies possessing an atmosphere, as in the case of most planets, can be achieved through the use of conventional aerodynamic devices such as parachutes, stabilizing fins, and so forth. However, unidirectional penetrometers designed to study surfaces having little or no atmosphere, as in the case of the moon, must depend upon other techniques for achieving stability. The stability aspect of unidirectional systems in a tenuous atmospheric environment is also discussed in the appendix.

In summary, the design of penetrometer devices requires that consideration be given to certain practical problem areas. Those of omnidirectional systems are basically developmental whereas those of unidirectional systems relate to increased experimental complexity. The unidirectional system can be realized in hardware form for immediate application and the more desirable omnidirectional system, presently under development, should be achieved in the near future.

Relay Craft

General considerations.- In order to obtain the impact acceleration information from the penetrometers, the data receiving station must be within the transmission field of the penetrometer telemetry system. However, penetrometers of practical size are limited by available power, antenna efficiency, and so forth; hence, it is not feasible to transmit their impact acceleration signals for extensive distances. Therefore, for applications where the receiving station is beyond the penetrometer transmission range, as for transmission to lunar or planetary orbiting vehicles or to earth, provisions must be made to intercept and retransmit the penetrometer signals to the distant receiving station. A vehicle which fulfills these requirements is hereinafter referred to as a relay craft. In remote penetrometer experiments, it would appear most practical to provide the penetrometer payload carrier with the capability to serve as a relay craft since this structure would be in the vicinity of the penetrometer impact area by virtue of its basic function.

In order to fulfill its mission, the relay craft must receive the penetrometer acceleration data and retransmit those data in a form suitable for reception at distant receiving stations. When the range of the receiving station is moderate, as, for example, a parent spacecraft within several hundred miles, the relay craft may simply amplify and redirect the penetrometer signals. When the receiver is at great distances from the relay craft, as for transmissions to earth from the vicinity of the moon or a planet, data signal processing may also be required. The data processing, in effect, exchanges the peak power requirement of instantaneous data transmission for longer transmission time; thereby the demands placed upon the power supply are decreased. An example of a data processing technique is presented in the appendix.

Design considerations.- The purpose of the relay craft has been previously defined as a means to extend the transmission range of the penetrometers so that they can be used to obtain impact acceleration signals at great distances from the receiving station. Two general concepts are considered, both employing the penetrometer payload carrier as the relay craft. In the first concept the penetrometer payload carrier serves as a relay craft prior to impacting or landing on the surface undergoing evaluation, and in the second concept the penetrometer payload carrier performs the relay operations after landing and while situated on the surface. Operations of the relay craft for the first concept do not depend upon a subsequent successful landing of that craft on the surface being investigated because its operations are accomplished during the interval between penetrometer impacts on the surface and relay-craft contact with the surface. Therefore, for this concept, sufficient time must be provided for the relay craft to receive, condition, and retransmit the impact acceleration information generated by the impacting penetrometers. Ample time for relay operations can be readily obtained by holding the relay craft aloft through the use of auxiliary devices such as retrorockets, parachutes, and so forth, which reduce the rate of descent of the craft after the penetrometers have been launched.

The second concept, wherein the relay craft is stationed on the surface undergoing evaluation during the penetrometer impacts, does not present any time limitation for relaying the impact acceleration data; however, it does pose problems which are related to the nature of the surface. Unlike the above-surface relay craft, this concept demands a successful landing on an unknown surface with the craft operationally capable of both receiving and transmitting data. The success of such conceptual operations is dependent upon the surrounding surface terrain. Should the space between the impacting penetrometers and the relay craft be interrupted by surface irregularities, penetrometer transmissions could be deflected or absorbed and never reach the relay craft. A physical transmission link such as a trailing wire could solve this problem but possibly at the expense of a reduction in the surface exploration area and/or increased operational complexity attendant with long-line trailing-wire systems.

SPACECRAFT APPLICATIONS

In view of the apparent capability of the penetrometer technique to evaluate certain physical properties of the surface of the moon or a planet or to serve as a means for sounding those surfaces in support of manned landings, the following paragraphs briefly review the results of a study directed toward possible applications of this technique to payloads of various spacecraft. For the purposes of this study, the penetrometer payload is applied to only those spacecraft presently in use or being considered for use in lunar exploration, however applications to other spacecraft and to other surfaces appear equally practical. Consideration is given to the application of the penetrometer technique as an experiment aboard the unmanned Ranger and Surveyor and as a sounding device adapted to manned spacecraft, such as Apollo, to evaluate prospective landing sites.

Unmanned Spacecraft

Ranger spacecraft.- A penetrometer experiment as a payload for the Ranger spacecraft would necessarily be the primary payload because of spacecraft volume and weight limitations. Two applications to Ranger are considered, and for each the experiment is designed to the same restraints specified for the seismometer experiment of Rangers 3 to 5. In the first application, penetrometers are released in free fall from a relay craft hovering just above the lunar surface and in the other application the penetrometers are ejected from the relay craft after it has come to rest on the lunar surface.

A payload designed to release penetrometers from a relay craft essentially hovering above the lunar surface, as depicted by the sketch in figure 3, requires a slightly different terminal trajectory than that programed for the seismometer experiment of Rangers 3 to 5. Modifications to the trajectory are necessary to provide control over various penetrometer impact conditions and to allow sufficient time for data processing and retransmission. As shown in figure 4, which presents the approximate terminal trajectory details of Rangers 3 to 5 and one possible trajectory of a penetrometer payload, the Ranger seismometer free-falls to the lunar surface following burnout of the retrorocket motor (defined herein as the primary retrorocket) at a lunar altitude of approximately 1100 feet. The modifications to this trajectory for the penetrometer payload include early primary retrorocket firing to permit burnout at a lunar altitude of 3000 feet, and subsequent ignition of a small secondary retrorocket motor included in the penetrometer payload. The purpose of this secondary retrorocket is to hold the relay craft above the lunar surface, within the transmission field of the penetrometer telemetry system for the required time interval.

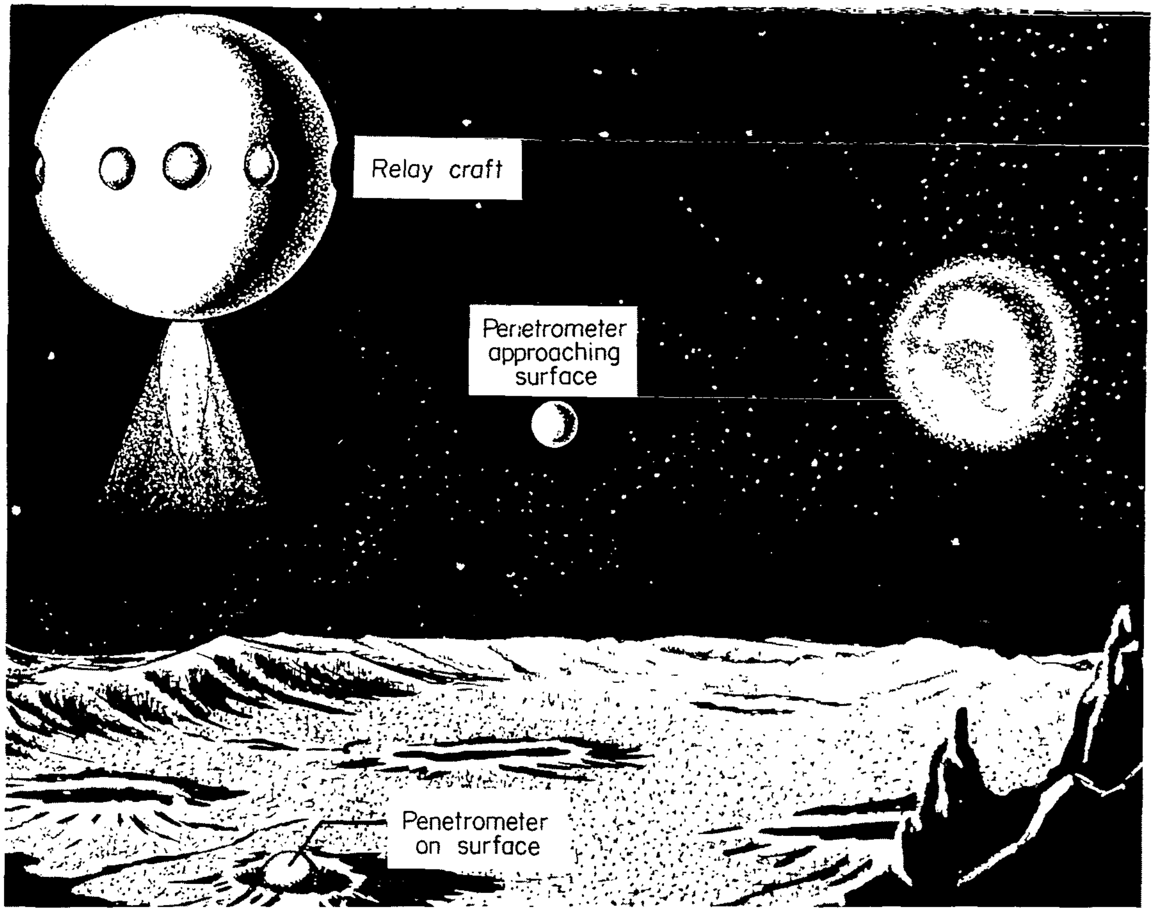


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Figure 3.- Technique for penetrometer operations with the relay craft above the lunar surface.

Since there exists a wide variety of small retrorockets capable of fulfilling the secondary retrorocket requirements and since the timing of terminal events is variable, there exists numerous possible relay-craft trajectories for a penetrometer payload aboard the Ranger spacecraft. For the trajectory illustrated in figure 4, a secondary retrorocket having a thrust-weight ratio of 4 and a 10-second burning time is ignited at 2400 feet above the lunar surface. Considering the previously noted requirements for a hovering relay craft, it is apparent that the use of such a secondary retrorocket results in a relay-craft trajectory which would accommodate at least all penetrometers released during the first 8 seconds of the secondary retrorocket burning time. These penetrometer releases are illustrated in greater detail in figure 5 where the time and altitude relationships are presented for the relay craft and penetrometers released at the time of secondary retrorocket ignition and 8 seconds later. Impact acceleration signals from penetrometers released during this 8-second time interval would be retransmitted to earth. This figure shows that the distances from the penetrometer to the relay craft are well within the transmission range of practical penetrometer capabilities (available power, antenna efficiency, etc.) and that ample time is provided for data processing and retransmission, which requires only a few seconds. Other trajectories for similar penetrometer payloads aboard the Ranger spacecraft are discussed in the appendix together with details of hardware components.

In the second application of penetrometers as a Ranger payload, experimental operations are conducted from the surface of the moon. This particular application was proposed in reference 3 which also reports the results of a detailed study of the technique. It consists of replacing the inner portion of the seismometer experiment of Rangers 3 to 5 with a penetrometer payload while retaining the outer shell, that is, the balsa-wood impact limiter, of the seismometer capsule. The method of delivering the payload to the lunar surface is identical to that developed for the seismometer. (See fig. 4.) Upon coming to rest on the surface, the impact limiter is removed and the inner penetrometer payload assembly is erected on the lunar vertical. An antenna for data transmissions to earth is erected and, as schematically illustrated in figure 6, the penetrometer payload is prepared to launch the penetrometers. The design employs spherical omnidirectional penetrometers which are individually launched from the parent capsule. Signals from the penetrometers pass to the relay craft by means of trailing wires and are then transmitted to earth.

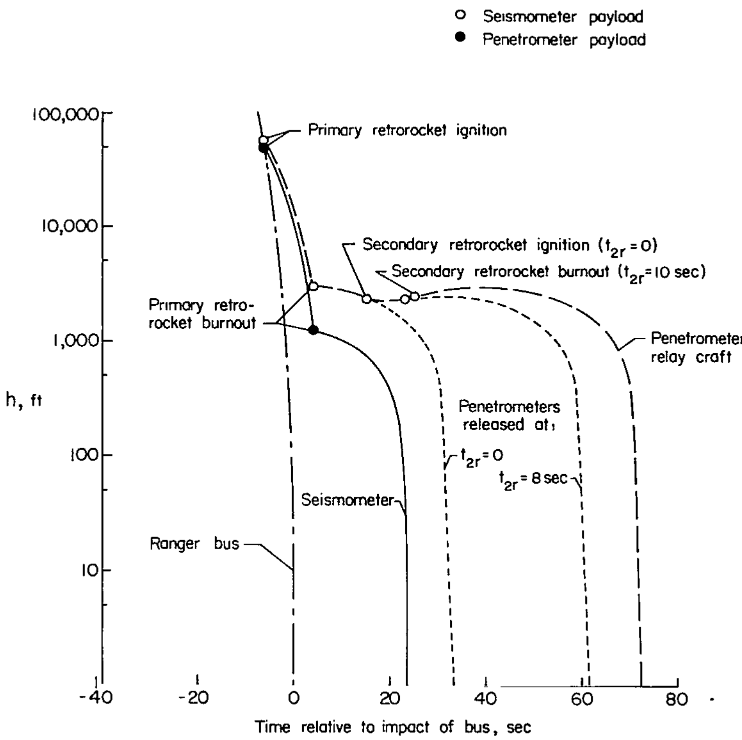

Figure 4.- Terminal trajectory details of Rangers 3 to 5 showing possible application to a penetrometer payload.

The two aforementioned techniques illustrate application of penetrometers to obtain data on characteristics of the lunar surface when employed as the primary payload of the Ranger spacecraft. Since the Ranger spacecraft imposes strict payload volume and weight limitations, a more extensive evaluation of surface characteristics would be afforded through the use of larger, more sophisticated vehicles, such as Surveyor, which could be soft-landed on the surface.

Surveyor spacecraft.- In view of the less stringent weight and volume limitations imposed by the Surveyor, this spacecraft could be adapted to include a penetrometer experiment as a secondary payload. As for Ranger, two penetrometer applications are considered herein, both taking advantage of the Surveyor data transmission equipment to relay the penetrometer impact signals

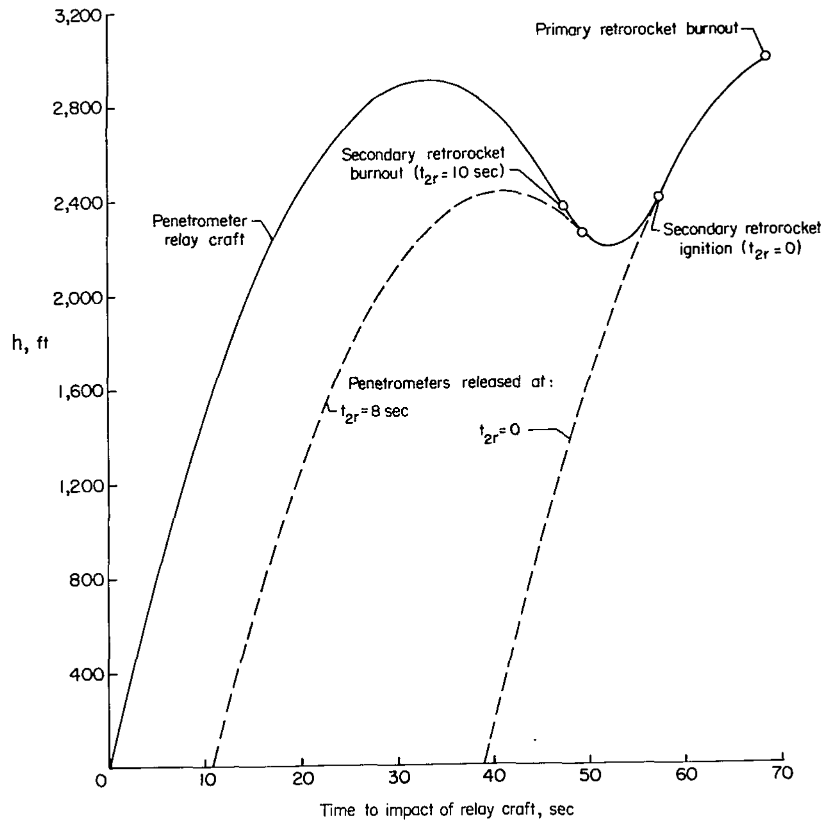

Figure 5.- Terminal trajectory details of a penetrometer payload as applied to the Ranger spacecraft.

to earth receiving stations. The two applications include the release of penetrometers from the spacecraft during the terminal phase of the vehicle trajectory and the launching of penetrometers from the spacecraft following a soft landing on the lunar surface.

A typical terminal descent trajectory of the Surveyor spacecraft is presented in figure 7 and includes, in chronological sequence: a main retrophase which positions the craft at approximately 27,000 feet above the lunar surface at burnout traveling with a velocity vector of about 350 fps, a vernier descent phase during which lateral velocity is nulled and vertical velocity is retarded such that at about 40 feet above the lunar surface the spacecraft descent velocity is approximately 5 fps, a constant descent velocity of about 5 fps to approximately 13 feet above the lunar surface, and free fall to lunar surface contact. The altitude time history of this descent trajectory is presented in figure 8 where time is related to the instant of spacecraft touchdown. The terminal phase of the Surveyor landing, as illustrated in figures 7 and 8, permits considerable latitude in the programing of penetrometer releases. Figures 7 and 8 depict penetrometer trajectories for releases at arbitrarily selected lunar altitudes of 100, 1000, and 5000 feet. The two figures indicate that no alterations to the programed flight trajectory of the Surveyor spacecraft would be required to satisfactorily perform a penetrometer experiment. Penetrometers released from Surveyor between lunar altitudes of 5000 feet and 100 feet would have acceptable impact velocities, and sufficient time would be available for relay operations by the spacecraft prior to touchdown. The range of impact velocities would extend from approximately 40 to 330 fps, corresponding to releases from 100 feet to 5000 feet, respectively. Such impact velocities would not impose structural loadings requiring undue ruggedization of the penetrometers and, furthermore, are within a range compatible with straightforward calibration procedures. The time difference between penetrometer impact and spacecraft touchdown is more than adequate for all releases above a lunar altitude of approximately 100 feet and increases with altitude.

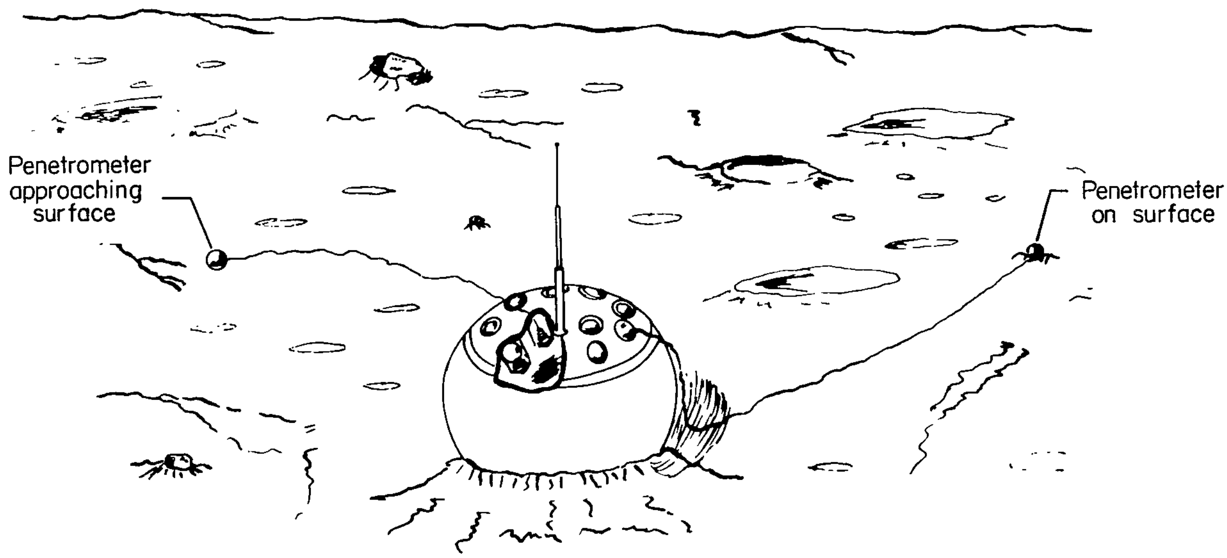

Figure 6.- Technique for penetrometer operations conducted from a lunar-based relay craft.

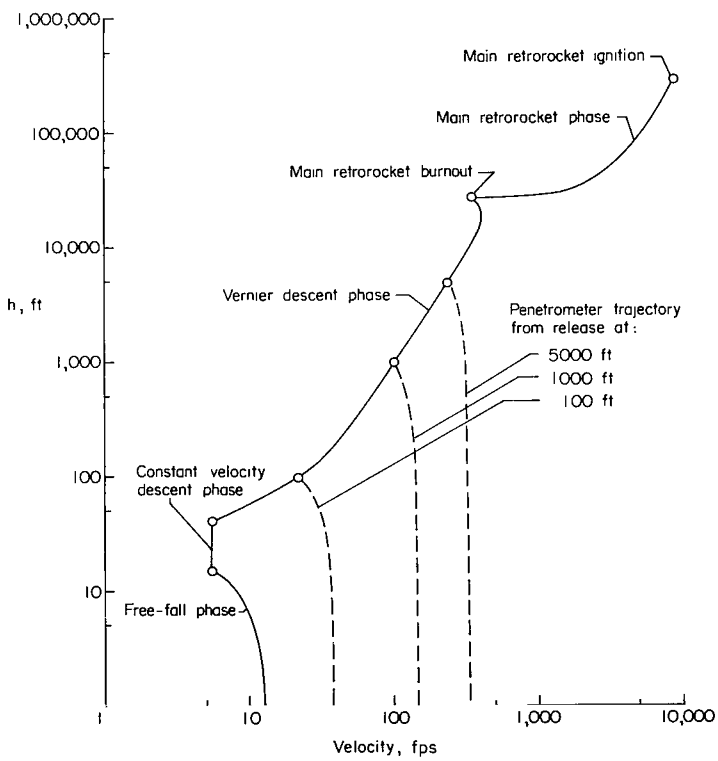

Figure 7.- Terminal descent phases of Surveyor spacecraft showing possible penetrometer deployment.

However, signals from the impacting penetrometers would be transmitted to the spacecraft through the exhaust of the vernier rocket motors and consideration must be given to possible effects of the exhaust products on this transmission.

The application of penetrometer systems as secondary payloads to lunar-based Surveyor spacecraft is not significantly unlike the application to lunar-based penetrometer payloads of Ranger spacecraft previously discussed. However, like the lunar-based Ranger penetrometer payload, the method of penetrometer deployment is subject to the demands placed upon any vehicle required to operate from the lunar surface. (See section entitled "Relay Craft.") Penetrometer deployment from such relay craft could include free fall or propelled launches to the lunar surface with signals from the penetrometers passing

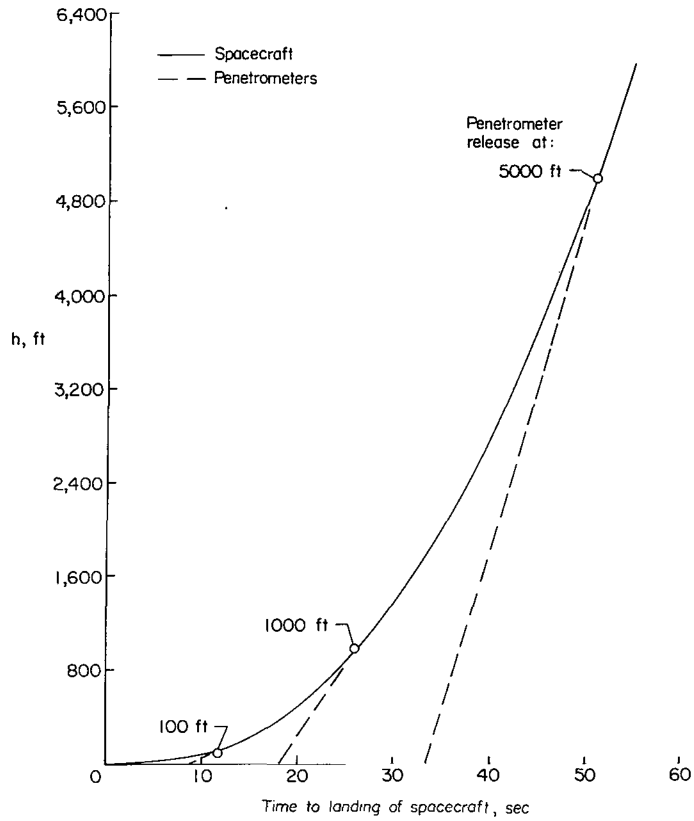

Figure 8.- Terminal trajectory details of Surveyor spacecraft showing possible penetrometer deployment.

to the relay craft either by means of telemetry or trailing-wire links for eventual retransmission to earth-based receiving stations.

Manned Spacecraft

Penetrometers show promise as sounding devices for manned spacecraft to evaluate immediate prospective landing sites. Information gained from impacting penetrometers would aid the astronaut in deciding whether the prospective site is suitable for a spacecraft landing. The operational procedure of the penetrometer technique in the manned lunar landing phase of the Apollo mission, for example, would be very similar to that for unmanned Ranger and Surveyor spacecraft designed to perform penetrometer experiments from above the lunar surface. For the unmanned missions, a relay craft serves to retransmit the penetrometer impact information to receiving stations on earth or to a parent lunar orbiter. However, for manned missions, the spacecraft itself is the receiving station and the penetrometer signals would be presented to the astronaut for his immediate use and for retransmission to earth as desired.

The application of penetrometer systems to manned spacecraft does not necessarily require the landing vehicle to be in its terminal phase before obtaining a landing-site evaluation. For example, the manned spacecraft could release a number of probes from lunar orbit that would house penetrometers for deployment over different areas of the lunar surface. In such cases, the probes are simply unmanned penetrometer payloads which would provide the necessary control over the penetrometer impact velocity and serve as the relay craft to retransmit the penetrometer impact information to the orbiting astronaut and/or to earth. The decision could then be made as to which of the sounded areas would be most suitable for spacecraft landing. To aid in guiding the astronaut to the selected site, one attractive scheme would consist of equipping the probes with impact survivable homing devices such as radio-beacon transponders.

CONCLUDING REMARKS

Basic impact research has shown that an analysis of accelerations produced during the impact of suitably instrumented penetrometers can provide needed information on physical characteristics of a remote surface such as that of the moon or the planets. Practical penetrometer systems can be designed to evaluate such surface properties as hardness or penetrability and, possibly, bearing strength. One system, omnidirectional in character, has been conceived but its operational use depends upon completion of the development of a suitable omnidirectional acceleration sensor. A unidirectional system is shown to be attainable within present-day technology at the expense of some increase in experimental complexity. Both systems are appropriate to unmanned exploratory missions and to manned reconnaissance or landing missions.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., June 1, 1964.

APPENDIX

DETAILED APPLICATION OF THE PENETROMETER TECHNIQUE TO THE RANGER PROGRAM

This appendix presents a description of the scope and concepts of a two-phase study undertaken to examine the application of the penetrometer technique to payloads for the Ranger spacecraft. The first phase employs omnidirectional penetrometers and embraces several areas necessitating further developmental efforts. The second phase treats a unidirectional penetrometer system suitable for immediate application to a Ranger payload. The scope of both phases contained several basic guiding principles for penetrometer-system design which included: (1) adherence to weight, volume, and structural interface requirements previously established for the seismometer payload of Rangers 3 to 5; (2) operations independent of lunar-surface conditions; (3) no requirements to successfully land a vehicle on the lunar surface; (4) acquisition of impact information which describes the surface structure at various points over a large territorial area; and (5) mechanical and electronic simplicity consistent with obtaining intelligible information. The results of the study for both phases are presented because the details of this application are appropriate to possible future applications of the penetrometer technique to other spacecraft.

Omnidirectional System

A photograph of a model of the omnidirectional penetrometer payload as applied to the Ranger spacecraft is presented in figure 9 together with that of the seismometer for comparison purposes. The photograph illustrates the nature and interface compatibility with the Ranger seismometer payload. The figure also identifies major components of the spacecraft configuration for a penetrometer experiment - such as the bus, which is the supporting structure for the experiment during the earth-to-moon transit; the retrorocket motor, again referred to as the primary retrorocket, which is used to slow the payload near the lunar surface from a velocity of about 9000 fps to a nominal value of zero; and the payload, which consists of the relay craft, equatorially mounted spherical penetrometers, and a secondary retrorocket motor.

At burnout of the primary retrorocket, the penetrometer payload is separated from the spent retrorocket by the same apparatus and techniques used for the seismometer payload and follows a trajectory such as the one illustrated in figure 10. The penetrometer payload trajectory described by figure 10 and illustrated in more detail by figure 11 is somewhat different from that described in the text for Ranger penetrometer payloads (figs. 4 and 5). Since a number of trajectories for penetrometer payloads are available due to the flexibility in the event-timing sequence and the wide choice of penetrometer payload secondary retrorockets, the selected trajectory for a given payload is a result of a number of considerations and compromises. Among these are various physical parameters of the payload such as weight and spin-up rate, power and transmission time tradeoffs, and penetrometer impact velocity and dispersion.

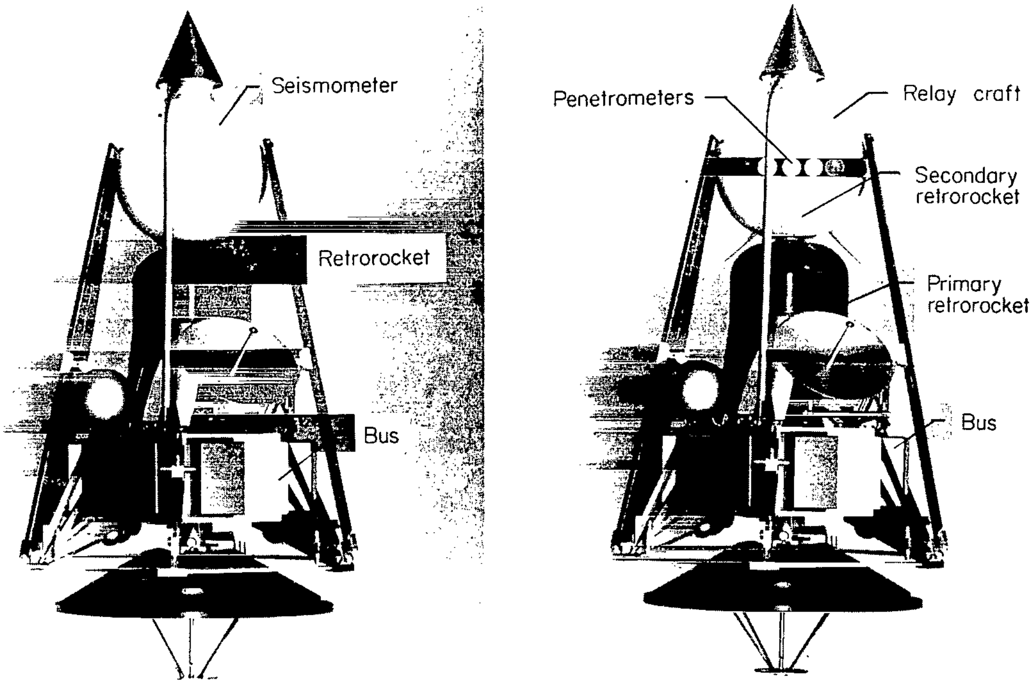

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Figure 9.- Photographs of Ranger spacecraft models showing seismometer and possible omni-directional penetrometer payloads.

The trajectory for this application was chosen so as to yield information on the nature of the lunar surface from 16 penetrometers impacting that surface over an area of about 1/2 mile in diameter while employing a secondary retro-rocket having a burning time of 10 seconds and a thrust-weight ratio of 2 in the moon's gravitational field. For purposes of this experiment, the only change required in the operational aspects of the spacecraft used for Rangers 3 to 5 is to set the radar altimeter ahead about 1/2 second. Thus, separation of the bus, spin-up of the primary retrorocket and payload, and ignition and burn-out of the primary retrorocket will occur approximately 1/2 second earlier than the corresponding times for Rangers 3 to 5. Consequently, the altitude of the penetrometer payload above the lunar surface at primary retrorocket burnout will be about 5600 feet as compared to about 1100 feet for the seismometer payload. However, the payload residual velocities (rms vertical velocity of 23.8 fps and an rms horizontal velocity of 74.5 fps) and inclination of the velocity vector with respect to the lunar vertical at burnout will be about the same for both payloads.

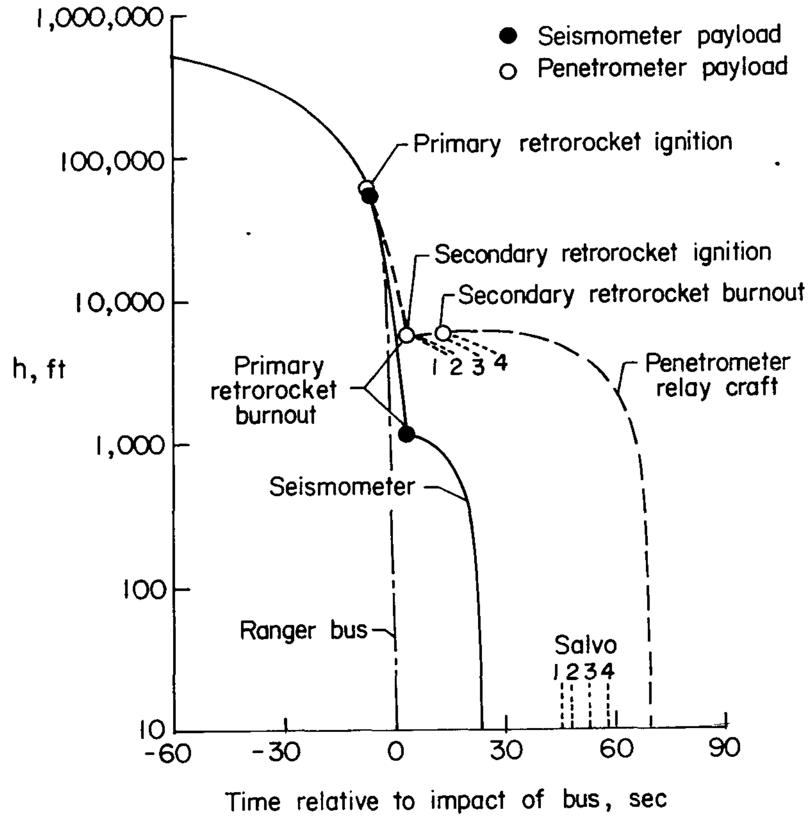

Figure 10.- Terminal trajectory details of Ranger spacecraft seismometer and possible omnidirectional penetrometer payloads.

Mode of operation.- At the instant of separation of the payload from the spent primary retrorocket, the secondary retrorocket is fired. Simultaneously, the first salvo of four penetrometers is released and allowed to free-fall to the lunar surface as shown in figure 11, which shows the terminal trajectories of the relay craft and the four salvos of penetrometers. Because of the thrust of the secondary retrorocket, the relay craft and remaining penetrometers cease their vertical descent approximately 4 seconds after retrorocket ignition and gradually increase in altitude. The remaining three salvos of penetrometers are released at intervals of 2 seconds requiring 6 seconds of the 10-second retroburning time. Like the penetrometers which preceded it, the relay craft at secondary retrorocket burnout then begins to free-fall to the lunar surface. Figure 11 also shows the impact times of the various salvos and the corresponding altitudes of the relay craft which vary from 4500 feet at impact of the first salvo to about 2500 feet at impact of the last salvo.

Since the relay craft is spinning at about 285 rpm at the time of release of the penetrometers, the penetrometers leave the relay craft with a velocity parallel to the lunar surface of about 27 fps. Consequently the penetrometers associated with each salvo are separated by a distance of approximately

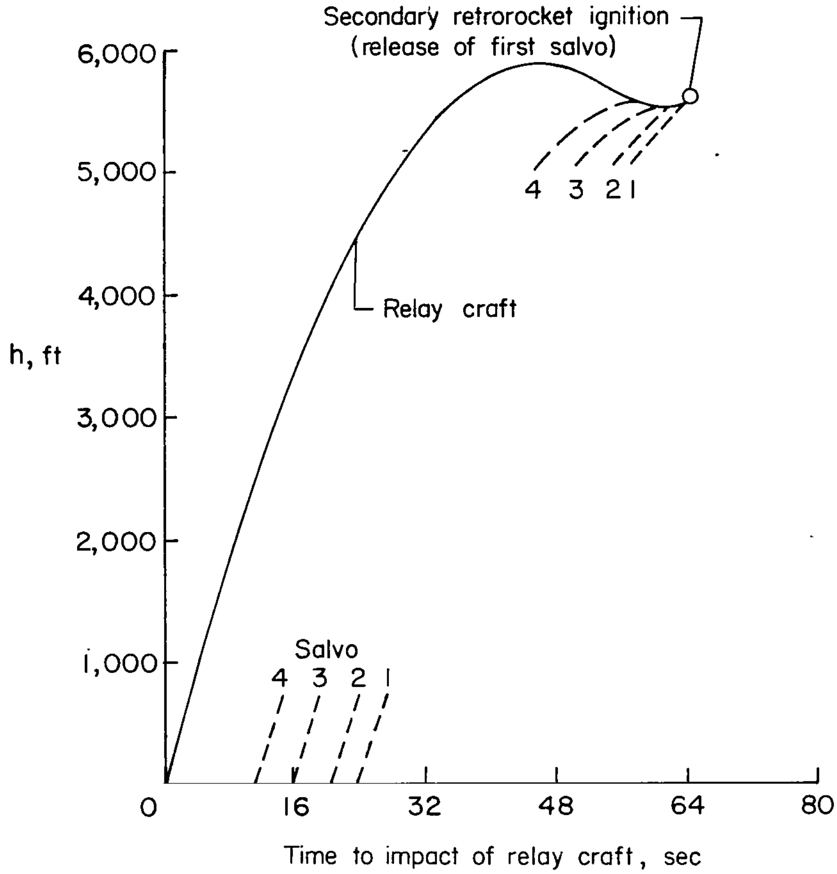

Figure 11.- Terminal trajectory details of possible omnidirectional penetrometer payload.

2200 feet upon impact. Figure 12 shows the dispersion distances as well as the vertical impact velocities for each salvo. The vertical impact velocities are shown to be nearly constant at about 250 fps.

Upon impact on the lunar surface, the acceleration signals from the penetrometers are transmitted to the relay craft and subsequently relayed to earth prior to impact of the relay craft. The design descriptions of the penetrometers and the relay craft are discussed in the sections which follow.

<u>Penetrometers</u>.- A block diagram of the proposed penetrometer instrumentation for the omnidirectional system is shown in figure 13. The output of an omnidirectional accelerometer is fed to signal-conditioning circuitry and then to a modulator-transmitter which excites an omnidirectional spherical antenna (hereinafter referred to as an antennasphere). At an arbitrarily selected frequency of 250 megacycles, a transmitter power output of 100 milliwatts is attainable which is more than sufficient for the programed transmission distance. The penetrometer power supply consists of a rechargeable battery capable of supplying 500 milliwatts. The penetrometer is packaged in the form of a sphere

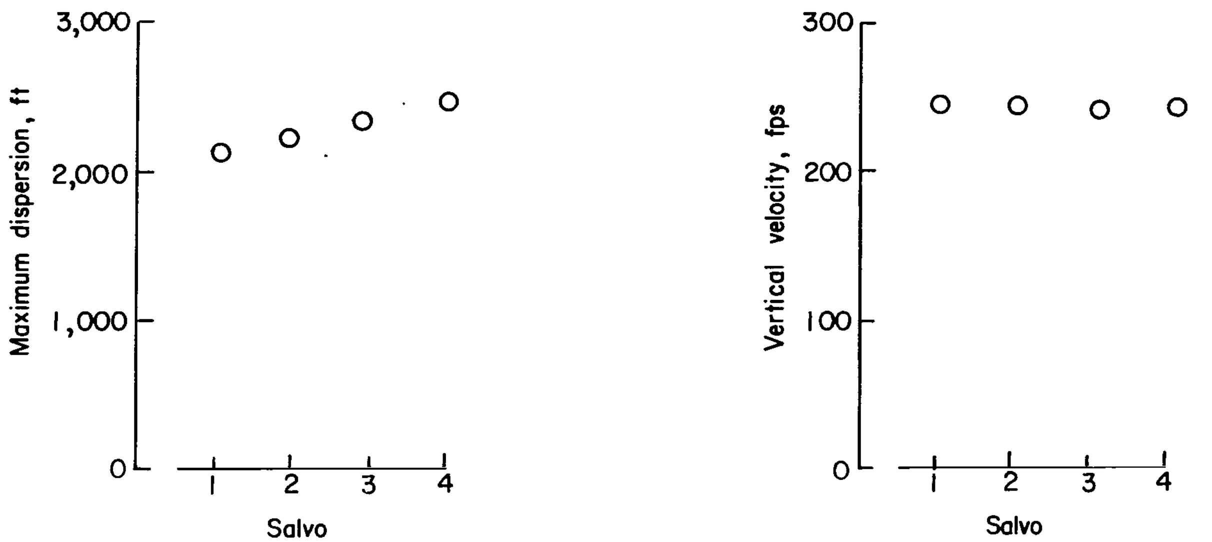

Figure 12.- Dispersion and velocity characteristics of omnidirectional penetrometers at impact.

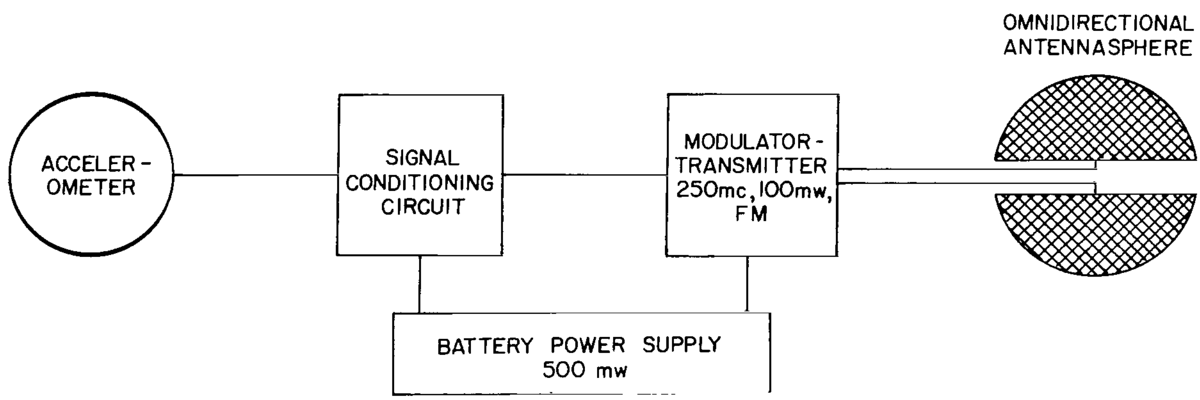

Figure 13.- Block diagram of possible omnidirectional penetrometer instrumentation.

about 3 inches in diameter, with the antennasphere encapsulated near the surface.

The penetrometer must be capable of performing during impact accelerations up to levels corresponding to those developed upon encountering the hardest anticipated surface. In order to determine the response characteristics, each penetrometer must undergo a dynamic performance calibration onto various terrestrial materials at impact velocities appropriate to the intended mission, prior to the flight. This calibration would also account for mechanical dynamic effects on the penetrometer structure. Thus, each penetrometer instrument can be considered a self-contained radiating acceleration transducer.

Table II presents a summary of radio-link performance considerations associated with the frequency modulated transmitting penetrometer instrument and

TABLE II

RADIO-LINK PERFORMANCE CONSIDERATIONS FOR OMNIDIRECTIONAL

PENETROMETER TO RELAY CRAFT

[250 megacycles, FM]

Penetrometer antenna gain	-12 db
Path loss (1 mile)	-85 db
Losses (polarization, line, etc.)	-4 db
Relay craft receiving antenna gain	1 db
Subtotal	-100 db
Required signal-noise ratio	15 db
Required performance	115 db
Receiver capability (bandwidth, 100 kc)	98 dbm
Transmitter power (100 mw)	20 dbm
Available performance	118 db
Performance excess	3 db

affecting the transmission from the penetrometer to the relay craft, which include an experimentally determined penetrometer antenna loss of 12 db; a calculated 1-mile link-path loss of 85 db; and losses due to polarization, antenna feed, and so forth, which may approach 4 db. Relay-craft antenna length and orientation is such as to allow a receiving antenna gain of at least 1 db. If a receiver output signal-noise ratio of 15 db is to be provided, the total performance requirement totals 115 db. A relay-craft receiver sensitivity of 98 dbm at 100 kc bandwidth and the previously mentioned 100-milliwatt transmitter power are readily attainable; these yield a total available performance of 118 db. Thus, the system provides a performance excess of at least 3 db.

The performance considerations of table II are conservative because no upper limit performance is demanded of any of the link components. However, the choice of operating frequency and the modulating technique and, hence, the performance requirements may change for particular missions - the selection being dependent on the variant parameters of the particular mission.

Relay craft.- The portion of the experimental payload which hovers above the lunar surface during the penetrometer impact period has been previously defined as a relay craft. The function of this apparatus is to receive the real-time analog data transmissions from the impacting penetrometers and retransmit this information at suitable frequency, power, and bandwidth to earth-based receiving stations, Deep Space Instrumentation Facility (DSIF). A conceptual sectional sketch of the 25-inch spherical relay craft is given in figure 14, and its functional operating sequence is given in block diagram form in figure 15. The analog data transmissions from the impacting penetrometers are received by the relay-craft receiving antenna system and are distributed by means of a multicoupler to as many receivers as there are penetrometers (16 for the mission described). Each receiver is tuned to the unique operating frequency of a penetrometer and these frequencies are sufficiently separated to minimize intermodulation. The receivers route the penetrometer signals to individual digitizing channels.

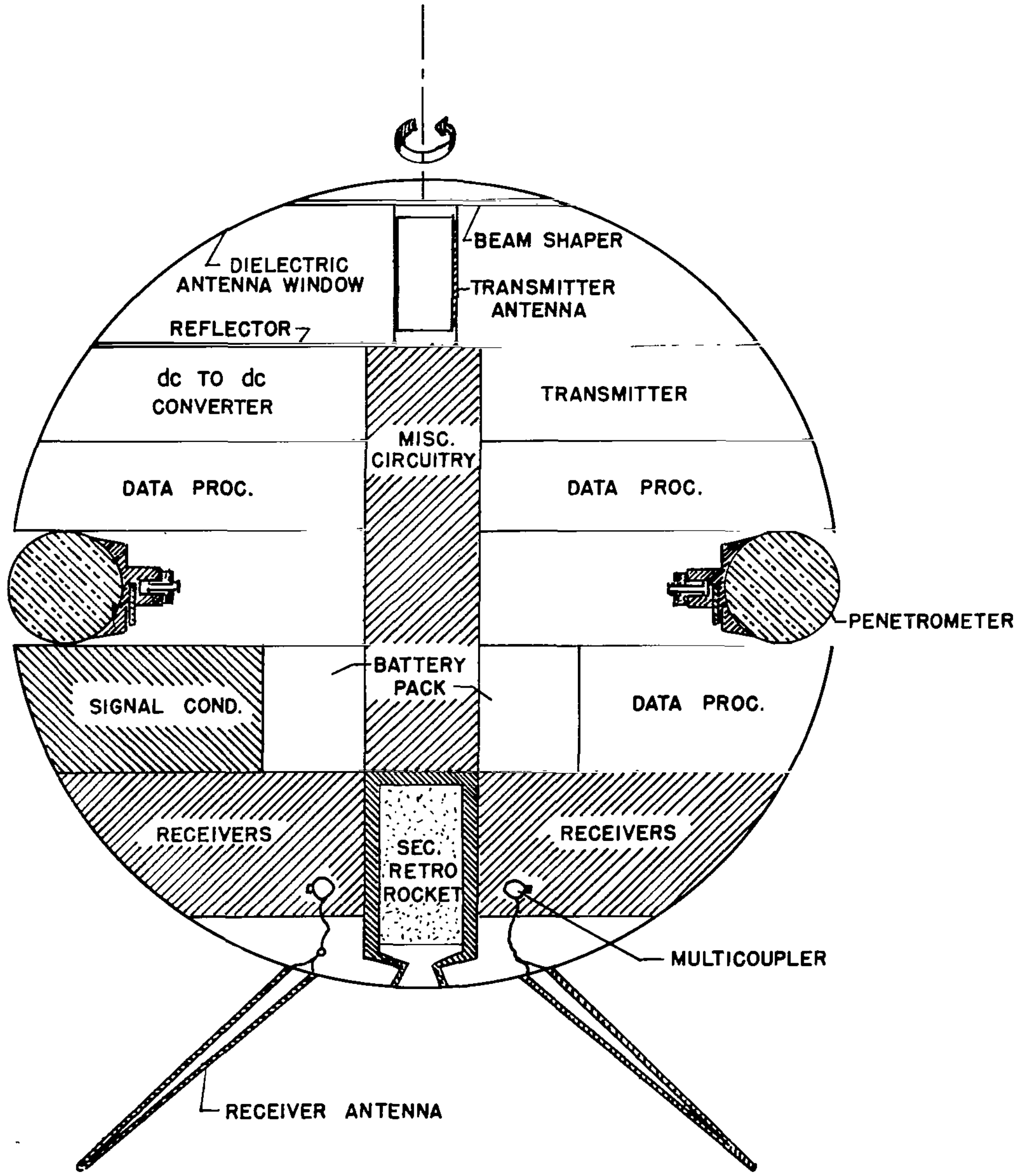

Figure 14.- Sectional sketch of relay craft for possible omnidirectional penetrometer payload.

Each digitizing channel converts the acceleration signal into a representative pulse train. The conversion process consists of either measuring the amplitude of this signal at selected instants of time or measuring the time at which the signal reaches preselected levels of amplitude. These measurements are converted to groups of pulses in binary code form which represent numerical values. The pulse groups are stored and subsequently read out by a programer. The programer rate of readout is much slower than the fastest acceleration pulse time which may occur; thus, an effective transmission bandwidth reduction is achieved commensurate with the spacecraft transmitting power limitations.

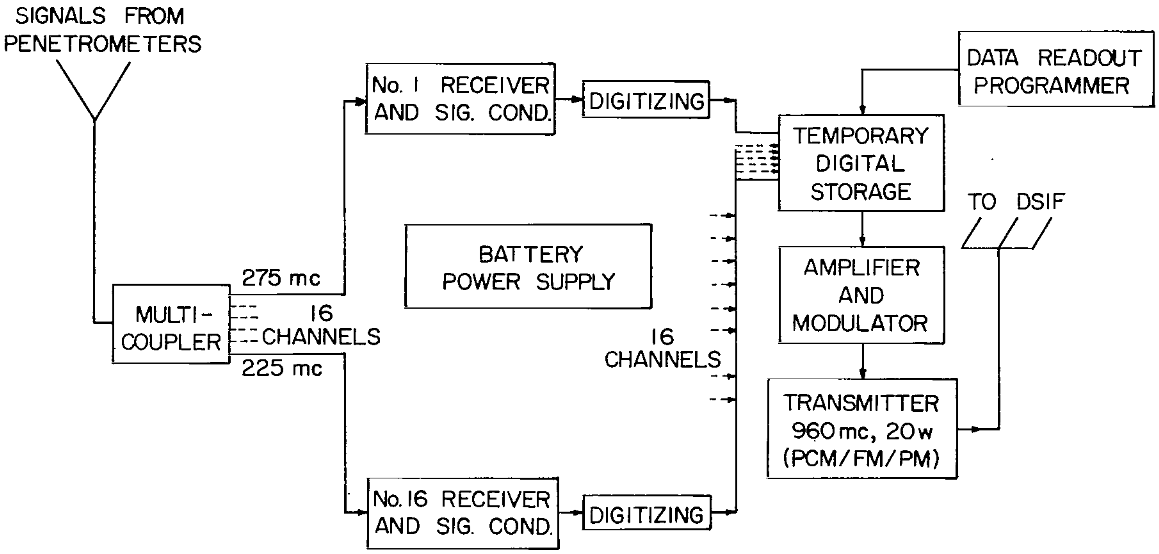

Figure 15.- Block diagram showing functional operating sequence of relay craft for possible omnidirectional penetrometer payload.

Further, since data readout is cyclic and nondestructive, data transmission redundancy is provided. The addition of appropriate synchronizing and identifying pulses to the data pulse code groups form a coded pulse train which modulates the 960 megacycle transmission to earth.

Table III presents a summary of the radio-link performance considerations associated with transmissions between the relay craft and the earth at a DSIF operating frequency of 960 megacycles. The table shows that a 20-watt 960-megacycle spacecraft transmitter provides signal power 15 db greater than

TABLE III

RADIO-LINK PERFORMANCE CONSIDERATIONS FOR

RELAY CRAFT TO EARTH

[960 megacycles, PCM/FM/PM]

Relay craft transmitting antenna gain	2 db
Path loss	-204 db
Losses (polarization, line, etc.)	-4 db
DSIF antenna gain	45 db
Subtotal	-161 db
Required signal-noise ratio	15 db
Required performance	176 db
Receiver capability (bandwidth, 3 kc)	138 dbm
Transmitter power (20 w)	43 dbm
Available performance	181 db
Performance excess	5 db

the noise power at DSIF with a performance excess of 5 db which includes minor losses not listed. The DSIF performance capability noted in the table is known from previous deep space missions and the relay-craft-equipment performance is well within present technology.

Relay craft which are required to transmit signals while spinning present a unique transmission problem due to the difficulties encountered in maintaining a transmission link line to the receiving station. Various means are available to provide high-gain spacecraft transmitting-antenna systems and substantially relieve radio-frequency power requirements; however, these antenna systems require active pointing and stabilization control which introduce complexity, reliability, and weight problems of their own. The best solution to this problem for a Ranger application appears to be a solid of revolution antenna-beam pattern employing low-gain fixed antenna structure and high levels of radio-frequency transmitted power. In such a system the antenna structure can be made very light in weight; furthermore the higher operating power levels would provide certain advantages to the experimental operational technique. For example, less precision is required of relay-craft maneuvers, the time required to establish the communication link between the relay craft and the receiving station may be reduced, and the probability of maintaining or quickly reacquiring tracking of relay-craft transmissions through relay-craft maneuvers and retrosequence events is improved. The additional battery weight required to accomplish the higher power level is not incompatible with the weight budget of the existing Ranger lunar exploratory spacecraft, and the reliability requirements are substantially less than alternative high-gain transmitting antenna systems. A properly shaped solid of revolution antenna-beam pattern can be sufficiently wide at earth intercept that several degrees of misalinement of the spinning relay craft can be tolerated without appreciable degradation in radio-link performance between the relay craft and the receiving station.

Unidirectional System

Since the omnidirectional penetrometer system still requires some development, a second study was initiated to devise a system concept utilizing available technology. This section of the appendix discusses the results of that study.

The payload configuration for this system, identical in overall dimensions to the omnidirectional system, consists of a 25-inch spherical relay craft equipped with a secondary retrorocket and 4 bullet-shaped unidirectional penetrometers. The shape of the penetrometers suggested for this system was selected to permit the application of available unidirectional techniques. The number of penetrometers was reduced from 16 for the omnidirectional system to 4 in order to reduce relay-craft instrumentation complexity while providing an adequate number of lunar surface measurements.

The sequence of events chosen for the terminal trajectory of the unidirectional system is similar to that for the omnidirectional system. The spacecraft radar altimeter is set such that the payload is positioned at 3000 feet above the lunar surface at primary retrorocket burnout with residual velocities identical to those for the seismometer and omnidirectional penetrometer system experiments. The trajectory selected for this payload subsequent to primary retrorocket burnout is given in figure 16 where the lunar altitude of the relay craft and the penetrometers is plotted relative to the impact time of the relay craft. Since all data transmission to earth ceases with relay-craft impact, sufficient time for relay transmissions of the penetrometer information is provided by delaying impact of the approximately 92-pound relay craft through the use of a secondary retrorocket having a burning time of 6 seconds and a thrust-weight ratio of 4 in the moon's gravitational field.

Mode of operation.- Immediately upon separation of the payload from the spent primary retrorocket at 3000 feet above the lunar surface, the four penetrometers are released and free-fall to impact. The relay craft is permitted to free-fall to 2000 feet at which altitude the secondary retrorocket is ignited. As illustrated in figure 16, the relay-craft descent is retarded by the action of the secondary retrorocket and it impacts the surface approximately 15 seconds after the penetrometers. The figure also shows that at the instant of penetrometer impact, the relay craft is at an altitude of about 1400 feet.

Since the payload is spinning at about 285 rpm at the time of penetrometer release, the penetrometers leave the payload with a horizontal velocity of about 27 fps and, therefore, are dispersed upon impact over a lunar surface area of about 820 feet in radius. The vertical impact velocity of the penetrometers due to the 3000-foot fall and the initial residual velocities is approximately 180 fps.

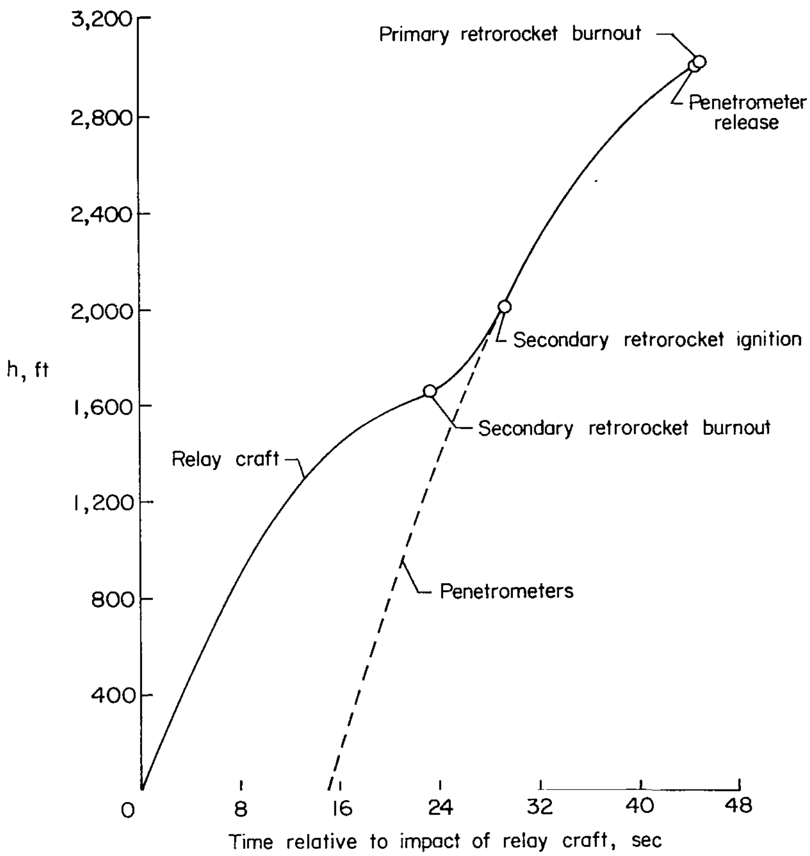

Figure 16.- Terminal trajectory details for the unidirectional penetrometer system.

As for the omnidirectional system, acceleration signals from the impacting penetrometers are transmitted to the relay craft and subsequently retransmitted to earth. Design considerations for the penetrometers and the relay craft of this unidirectional penetrometer system are discussed separately in the sections which follow.

Penetrometers.- The design considerations for the instrumentation of a unidirectional penetrometer are less stringent than those of the previously described omnidirectional penetrometer. First, unidirectionality permits the use of conventional uniaxial piezoelectric accelerometers as transducing elements. Second, the shaped device lends itself to the use of conventional antenna designs such as a simple dipole. The unidirectional concept also affords the possibility of improved shock protection to the components by orienting them so that the impact force is applied along a preferred axis and/or by providing shock absorption or impact limiting material along a preferred axis.

The consideration of these and other factors unique to the unidirectional penetrometer concept, led to the bullet-shaped penetrometer design illustrated in the sectional sketch of figure 17. This figure gives the overall dimensions of the penetrometer and indicates the various components of the system. Functionally this design is similar to that shown in the block diagram of figure 13 for the omnidirectional penetrometer. However, in the unidirectional concept the uniaxial accelerometer is substituted for the omnidirectional accelerometer system, and the metalized-skin vertical-dipole antenna is employed in lieu of the omnidirectional shell antennasphere. The operational sequence of the two penetrometer designs is the same with the exception that the impact force applied to the unidirectional system must be along the sensing axis of the accelerometer to avoid degradation of the response, which increases as the sine of the off-axis angle.

Performance characteristics of the radio link between the unidirectional penetrometer and the relay craft were evaluated, based upon the same operating conditions as those listed in table II for the omnidirectional penetrometer design. This evaluation showed that a performance margin improvement of about 5 db is realized in the unidirectional system due to the higher antenna gain attainable with the simpler antenna design.

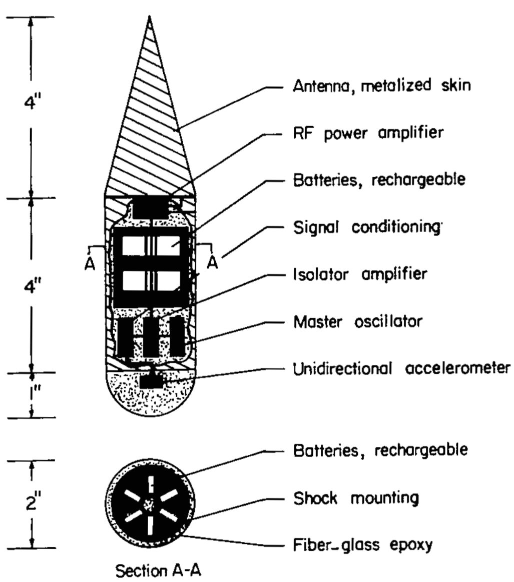

Figure 17.- Sectional sketch of unidirectional penetrometer.

Although the use of a unidirectional penetrometer permits an improvement in antenna gain, the antenna must be oriented with respect to the relay craft at the time of penetrometer telemetry transmissions. Figure 18 illustrates a typical pattern produced by such a unidirectional penetrometer dipole antenna and shows that, at the time of penetrometer impact, the relay craft should be positioned out of the region of reduced radiation which exists along the penetrometer longitudinal axis. Typical ground and altitude distances between the penetrometer and the relay craft during the time of signal transmission for the terminal trajectory considered for this case are also indicated on this figure and show that the relay craft is within the transmission zone of the penetrometer antenna pattern.

<u>Relay craft</u>.- The relay craft for the unidirectional penetrometer system is

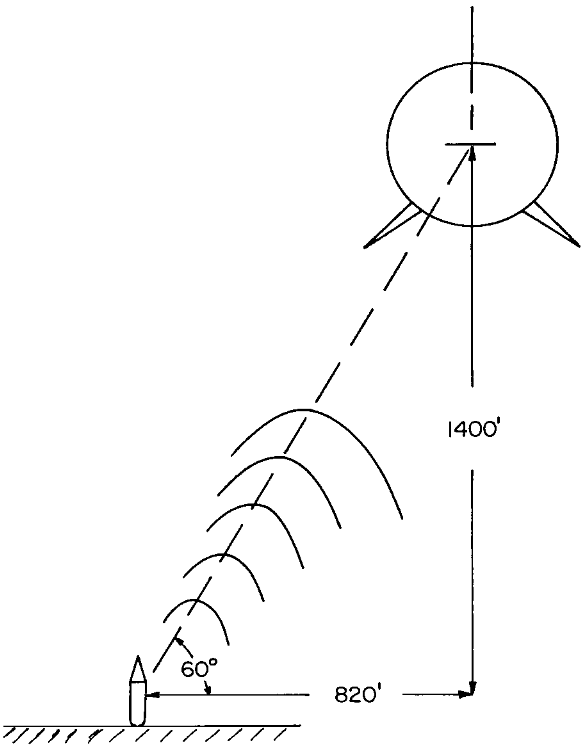

Figure 18.- Sketch of unidirectional-penetrometer antenna-transmission pattern showing geometry at impact.

essentially identical to the omnidirectional penetrometer system design of figure 14. The main difference is the reduction of the number of receivers from 16 to 4 because only 4 penetrometers were used. This reduction in the number of receivers simplifies the intercoupling problems of the receiving antenna, and the receiver and data-processing circuitries. The functional performance of this relay craft is identical to that of the omnidirectional penetrometer system. The characteristics for the radio-link performance between the relay craft and the earth as listed in table III, apply to both systems.

Although the bullet-shaped unidirectional penetrometer simplifies instrumentation problems, it is of paramount importance that its uniaxial acceleration sensor be properly oriented with the lunar surface during impact. Schemes utilizing aerodynamics for securing penetrometer attitude orientation are necessarily omitted for lunar applications due to the extremely low density of the moon's atmosphere. However, the low lunar atmospheric density suggests that, should the penetrometer be stable when released from the rotating payload, no external forces exist to upset that stability. Correspondingly, penetrometer release tests from a spinning platform were conducted in the 60-foot-diameter vacuum sphere at the Langley Research Center to evaluate penetrometer stability characteristics over the initial portion of the penetrometer free-fall flight path. These tests were conducted in a vacuum approaching 10^{-4} torr, and the flight path allowed by the confines of the test area was about $1\frac{1}{2}$ percent of the suggested trajectory distance and about 10 percent of the suggested trajectory flight time. The results of these tests indicated that bullet-shaped penetrometers can be released from a spinning vehicle such that attitude stability is maintained commensurate with the experiment requirements.

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